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Glossary of Optical Communication Terms

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16. Abstract

This glossary contains definitions of technical terms commonly used in the field of optical communication. It is intended for those who already have a technical background (engineers, scientists, and technicians), but are not familiar with the terminology of optical communication. Readers should note that for purposes of federal procurement, official definitions of terms related to telecommunication, of which optical communication is a subset, may be found in *Federal Standard 1037A, Glossary of Telecommunication Terms.* (A revision, FS-1037B, is in preparation.) The present document contains a number of entries not found in FS-1037B, and although not legally an arbiter of the official definitions found there, serves in many cases to amplify and/or clarify those definitions. Also, among the notes accompanying the definitions herein are a number of "mini-tutorials" that address certain matters which experience has shown to have led to confusion on the part of some individuals involved in one or more aspects of optical communication.

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EXECUTIVE SUMMARY

This glossary was first published in June 1986 by the Engineering Division of the FAA Technical Center, under the title *"Glossary of Fiber Optic Terms"* (Division Report CT-110-86-15). It has now been revised and expanded, and is made available for wider distribution. It is intended to be an introductory reference for those with a technical background (engineers, scientists, and technicians) who have an interest in optical communication, but are not familiar with some of the more common terms used in this field. For a more rigorous and complete treatment of the subject matter, the reader is directed to appropriate references.

GLOSSARY OF OPTICAL COMMUNICATION TERMS

abrasive Any of a number of hard materials, such as aluminum oxide, silicon carbide, diamond, etc., that are powdered and carefully graded according to particle size, and used to shape and/or finish optical elements, including the endfaces of optical fibers and connectors. *Note 1:* For finishing the endfaces of optical fiber connectors, abrasive particles are adhered to a substrate of plastic film, in a fashion after that of sandpaper. The film is in turn supported by a hard, flat plate. The connector is supported by a fixture that holds it securely in the proper position for finishing. The grinding motion may be performed manually or by a machine. Several successively finer grades are used until the connector is brought to the proper length and surface finish quality. *Note 2:* Abrasive materials differ from polishing materials in both particle size and the action they have on the workpiece. Abrasive particles are much larger than polishing particles, and remove glass by a fracturing action. Polishing materials promote a molecular surface flow of workpiece material to produce the final optical finish. The coarsest grades of microfinishing films used in finishing the endfaces of optical fibers produce microscopic surface fractures. The finest grades produce a smooth flow of surface material. *See also* **cleave, hockey puck, microfinishing film.**

absorption The conversion of radiant energy into other forms by interaction with matter. *See also* **absorption band, absorption coefficient, attenuation, attenuation coefficient.**

absorption band A spectral region in which the absorption coefficient reaches a relative maximum, by virtue of the physical properties of the matter in which the absorption process takes place. *See also* **absorption, absorption coefficient, attenuation, attenuation coefficient, passband.**

absorption coefficient The fraction of incident radiation absorbed by a material in a specified path length. *See also* **absorption, absorption band, attenuation, attenuation coefficient.**

acceptance angle Half the vertex angle of the largest cone within which optical power may be coupled into the bound modes of an optical waveguide. *See also* **numerical aperture.**

active star *See* **star coupler.**

all-glass fiber *Synonym* **all-silica fiber.**

all-silica fiber An optical fiber composed of a silica-based core and cladding. *Note:* The presence of a protective polymer overcoat does not disqualify a fiber as an all-silica fiber, nor does the presence of a tight buffer. *Synonym* **all-glass fiber.** *See also* **buffer (tube), optical fiber, plastic-clad-silica fiber, primary coating.**

amplifier *See* **fiber amplifier, optical repeater.**

angstrom (Å) An obsolete unit of length, equal to 10^{-10} meter. *Note:* It was formerly used to express optical wavelengths, and is still used in microscopy. *See also* **micrometer, nanometer.**

angular misalignment loss Optical power loss that occurs when the longitudinal axes of two connecting fibers (or a fiber and optical source) are coplanar, but not coincident; but rather are at a slight angle with respect to one other. *See also* **area loss, Fresnel reflection loss, gap loss, lateral offset loss, numerical aperture loss.**

APD *Abbreviation for* **avalanche photodiode.**

aramid (yarn) Generic name for a tough synthetic yarn (Du Pont Kevlar ™) that is often used in optical cable construction for the strength member, protective braid, and/or rip cord for jacket removal. *See also* **braid, rip cord, strength member.**

area loss A loss of optical power that occurs when optical fibers are joined by a splice or a pair of mated connectors, which loss is caused by any mismatch in size (area) or shape of the cross section of the cores of the mating fibers, or by their lateral misalignment. *Note 1:* Any of the above conditions may allow light from the core of the "transmitting" fiber to enter the cladding of the "receiving" fiber, where it is quickly lost. *Note 2:* Area loss may be dependent on the direction of propagation. For example, in coupling a signal from an optical fiber having a smaller core to an otherwise identical one having a larger core, there will be no area loss, but in the opposite direction, there will be area loss. *See also* **angular misalignment loss, Fresnel reflection loss, gap loss, lateral offset loss, numerical aperture loss.**

armor A component of a communication cable, which component is intended to protect the critical internal components (e.g., buffer tubes and fibers, in the case of optical cables) from damage from external mechanical attack (e.g., rodent attack, abrasion). *See also* **braid, strength member.**

attenuation A diminution of optical power, usually expressed in decibels (dB). *Note:* The term *"attenuation"* is often used erroneously as a synonym for *"attenuation* *coefficient."* *See also* **absorption, absorption band, absorption coefficient, attenuation coefficient, attenuation-limited operation.**

attenuation coefficient The rate of diminution of optical power in a unit distance along an optical fiber. *Note:* It is usually expressed in decibels (dB) per kilometer. *See also* **absorption, absorption band, absorption coefficient, attenuation, attenuation-limited operation.**

attenuation-limited operation The condition that prevails when attenuation, rather than bandwidth, limits the performance of a communication link. *Note 1:* For example, in a given digital link, for a specified bit rate, the bit-error ratio (BER) depends on the received optical power level (i.e., the number of photons per bit). The permissible BER limits the optical power budget (the maximum signal loss that can be tolerated). *Note 2:* The usual commercial practice is to specify a power budget that will support a BER of 10^{-9} or better. *See also* **absorption, absorption band, absorption coefficient, attenuation, attenuation coefficient, bandwidth, bandwidth·distance product, bandwidth-limited operation, optical power budget.**

avalanche multiplication A current-multiplying phenomenon that occurs in a semiconductor photodiode that is reverse-biased just below its breakdown voltage. *Note:* Under such a condition, electrons (photocurrent carriers) are swept across the junction with sufficient energy to ionize additional bonds, creating additional electron-hole pairs in a regenerative action. *See also* **avalanche photodiode (APD), dark current, photocurrent, photodiode.**

avalanche photodiode (APD) A solid-state photodiode that takes advantage of avalanche multiplication of the photocurrent. *See also* **avalanche multiplication, dark current, germanium photodiode, photodiode, positive-intrinsic-negative (PIN) diode, silicon photodiode.**

axial ray A ray that travels along (i.e., is coincident with) the optical axis of a fiber. *See also* **cladding mode, leaky ray, meridional ray, ray, skew ray.**

backscattering Scattering of light in a direction having a component opposite its original direction of propagation. *See also* **attenuation, attenuation coefficient, scattering.**

bandwidth 1. Of an optical fiber, a figure of merit that denotes the information-carrying capacity of the fiber. *Note 1:* The term *"bandwidth,"* as applied to an optical fiber, refers to the lowest modulation frequency at which the peak-to-valley amplitude (power) difference of an intensity-modulated monochromatic optical signal decreases, at the output of the fiber, to a specified fraction (usually one-half) of the amplitude (power) difference, also at the output of the fiber, of a nearly-zero modulation frequency, both frequencies having the same modulation amplitude (peak-to-valley difference) at the input. *Note 2:* In multimode fibers, multimode distortion is often the most significant parameter limiting fiber bandwidth, although material dispersion may also play a significant role, especially in the first (850-nm) window. *Note 3:* In multimode fibers, the multimode-distortion-limited bandwidth (*"fiber bandwidth"* in advertising parlance) is customarily specified for a single wavelength, or an extremely narrow band of wavelengths. In practice, the optical source will have a finite line width. Laser diodes typically have a line width of several nanometers, FWHM. LEDs typically have a line width of 35 to 100 nanometers, FWHM. In practice, then, the effective fiber bandwidth, and hence, its risetime and falltime, with sources that have a relatively wide spectral width, will be lower than indicated by the specified fiber bandwidth. *Note 4:* The effective risetime of multimode fibers may be estimated fairly accurately as the square root of the sum of the squares of the multimode-distortion-limited risetime and the material-dispersion-limited risetime. *Note 5:* In single-mode fibers, material dispersion and waveguide dispersion are the most significant parameters affecting fiber bandwidth. Practical fibers are designed so that material dispersion and waveguide dispersion cancel one another at the wavelength of interest. *Note 6:* Regarding effective fiber bandwidth as it affects overall communication system performance, it should be recognized that optical detectors such as PIN diodes are square-law devices. Their output photocurrent is proportional to the detected optical power. But because electrical power is proportional to the square of the current, when the optical power/modulation level drops to one-half of its initial value (a 3-dB decrease), the electrical power/modulation level of the detected signal drops to one-quarter of its initial value (a 6-dB decrease). Therefore, at the modulation frequency which represents the 3-dB fiber bandwidth, the detected electrical signal will have decreased by 6 dB. 2. Loosely, *synonym for* **bandwidth·distance product**. 3. Of an electrical/electronic device, the lowest frequency at which the electrical transfer function of the device decreases to a specified fraction of the zero-frequency value, usually one-half the zero-frequency power level (3-dB decrease). 4. Of an electrical/electronic device, the difference in hertz between the lowest and highest frequencies at which the electrical transfer function of the device decreases to a specified fraction (usually one-half) of the peak value. *See also* **attenuation, attenuation-limited operation, bandwidth·distance product, bandwidth-limited operation, cutoff frequency, full width half maximum, passband, spectral width, transfer function.**

bandwidth·distance product Of an optical fiber, the product of the bandwidth, usually expressed in megahertz or gigahertz, and the length, usually expressed in kilometers, normalized to a one-kilometer length. *Note 1:* This is used as a figure of merit to express the information-carrying capacity of the fiber. *Note 2:* Unlike metallic conductors, the bandwidth of an optical fiber decreases nearly linearly with length, so that doubling the length will reduce the bandwidth only by a factor of approximately two. *Note 3:* The term *"bit-rate·distance product,"* an analogous term with application to digital communication, is beginning to appear in the literature. *Synonym* **band-**

width• length product. *See also* **bandwidth, bandwidth-limited operation, dispersion, distortion, modal distortion.**

bandwidth• length product *Synonym* **bandwidth• distance product**

bandwidth-limited operation The condition that prevails when bandwidth, rather than attenuation, limits the performance of a communication link. *Note 1:* The term is often applied to optical fibers, and refers to the case in which the fiber bandwidth, rather than its attenuation, limits the maximum length of the link for a given level of performance. *Note 2:* In optical fibers, *"dispersion-limited operation"* and *"multimode-distortion-limited operation"* are special cases of *"bandwidth-limited operation."* *See also* **attenuation-limited operation, bandwidth.**

baseband modulation Modulation of an optical source (LED or ILD) directly, without first modulating the signal of interest onto an electrical carrier wave. *See also* **bandwidth** (definition **2**, *Note 6*), **detection, detector, modulation, modulator**.

beam A column of light. *Note:* It may be parallel, diverging or converging. *See also* **acceptance angle, beam divergence, convergence, divergence, expanded-beam connector, f-number, vertex angle.**

beam divergence In optics, the angle subtended in a given plane by a diverging beam of light, measured between points having an intensity equal to a specified fraction of the maximum intensity. *Note:* This term is analogous to the term *"beamwidth"* as used in radio communication to denote the angle subtended by the 3-dB points of the radiation pattern of an antenna. *See also* **acceptance angle, beam, divergence, expanded-beam connector, f-number, vertex angle.**

beamwidth *See* **beam divergence.**

bidirectional transmission Simultaneous transmission of optical signals in opposite directions over a single fiber. *Note:* Such communication may employ the same wavelength or different wavelengths in opposite directions. This type of transmission exacts a penalty in terms of the required optical power (optical power budget) and/or data bit-error ratio. *See also* **backscattering, optical power budget, wavelength-division multiplexing.**

bit-rate• distance product *See* **bandwidth• distance product.**

bound mode Of an optical fiber, loosely, a mode that is confined to the core, thus supporting propagation with minimum loss. *Note:* Strictly speaking, in single-mode fibers, the one bound mode does have a significant fraction of its total energy traveling in the cladding. A treatment of this may be found in advanced references. *Synonym* **guided mode.** *See also* **cladding, cladding mode, core, leaky ray, Maxwell's equations, mode, radiation mode, ray, Snell's law.**

bound ray *Synonym* **guided ray.** *See* **bound mode.**

braid 1. An essential part of many optical cable designs, consisting of a layer of woven yarn. *Note 1:* In the case of single-fiber loose-buffered or two-fiber "zip-cord" loose-buffered optical cables, it is situated between the buffer tube and jacket. In the case of cables having multiple buffer tubes, it is usually situated between the inner jacket and outer jacket. **2.** Loosely, an unwoven parallel bundle of yarn situated around the tight buffer of a single-fiber or two-fiber "zip-cord" optical cable. *Note 1:* The braid serves to add tensile strength to the cable. The braid may also be anchored to an optical connector or splice organizer assembly to secure the end of the cable. *Note 2:* The braid is often of an aramid yarn. *See also* **armor.**

break out To separate the individual fibers or buffer tubes of an optical cable for the purpose of splicing or installing optical connectors. *Synonyms* **fan out, furcate.**

breakout cable A multifiber cable design in which individual fibers, usually tight-buffered, are surrounded by separate strength members and jackets, which are in turn enveloped by a common jacket. *Note 1:* Such a design facilitates easy installation of optical connectors. All that need be done to prepare the ends of the cable to receive connectors is to remove the outer jacket, exposing what are essentially individual single-fiber cables. *Note 2:* Because it tends to induce bends in the fibers, this cable design usually results in slightly higher transmission losses (for a given fiber) than loose-buffer designs. *Synonym* **fanout cable.** *See also* **break out, breakout kit, pigtail** (definition **2**).

breakout kit A kit of materials, composed of an outer jacket in which is contained a strength member consisting of a bundle of usually aramid yarn, which jacket and yarn may be slipped over a loose buffer tube containing a single fiber, to convert the buffer tube and fiber to a complete single-fiber cable to which an optical connector may be directly attached. *Note 1:* A heat-shrinkable plastic boot may also be used for cosmetic purposes, strain relief, and to seal the point where the individual cables so created, merge. *Note 2:* Use of a breakout kit enables an optical cable containing multiple loose buffer tubes to receive connectors without the splicing of pigtails. *See also* **break out, breakout cable, pigtail.**

buffer (tube) An essential component of many common optical cable designs, used to isolate the fiber from potential hazards, such as mechanical deformation, physical damage, chemical attack, etc., in the service environment. *Note 1:* The buffer takes one of two basic forms. The first, called a *"tight buffer,"* consists of an additional plastic coating, approximately one millimeter in outside diameter, that is in intimate contact with the fiber's primary polymer coating, in a fashion similar to electrical insulation on a wire. The tight buffer should not be confused with the fiber's primary polymer coating, which is applied to all fibers as part of the manufacturing process, regardless of the design of the cable in which they are to be used. The other basic form of buffer is called a *"loose buffer,"* or *"loose buffer tube."* This may be likened to a miniature plastic conduit, having an outside diameter of approximately two millimeters and an inside diameter several times the outside diameter of the fiber's primary polymer coating. The fiber lies loosely in this "mini-duct," hence the name "loose buffer tube." The loose buffer tube is often filled with a protective gel that resembles petroleum jelly. The gel lubricates and tends to float the fiber, and prevents water intrusion in the event the tube is breached. *Note 2:* More than one fiber may be enclosed by the same loose buffer tube. Six or more fibers per tube is not an uncommon arrangement. This is one method of obtaining a high fiber density while maintaining a small cable diameter. The primary polymer overcoat on each fiber isolates it optically from other fibers in the same tube. Individual fibers in the same tube may be distinguished by color coding of the primary polymer coating. *Note 3:* Multiple buffers (loose or tight) may be incorporated in one cable. *See also* **optical cable**.

cable *See* **optical cable**.

cladding The dielectric material surrounding the core of an optical fiber. *Note:* The cladding must have an index of refraction slightly lower than that of the core. It is usually made of glass in intimate contact with the core. It may also be of plastic (not to be confused with the primary polymer overcoat of a glass-clad fiber). In general, a plastic cladding results in a fiber that has poorer transmission performance than glass-clad fibers. *See also* **core, optical fiber, plastic-clad-silica fiber, primary coating**.

cladding mode An undesired mode that is confined to the cladding of an optical fiber by virtue of the fact that the cladding has a higher index of refraction than the surrounding medium (air or primary polymer overcoat). *Note:* Modern fibers have a primary polymer overcoat with an index of refraction that is slightly higher, rather than lower, than that of the cladding, in order to strip off cladding modes after only a few centimeters of propagation. *See also* **axial ray, cladding, leaky ray, Maxwell's equations, meridional ray, mode, primary coating, radiation mode, ray, skew ray, Snell's law, total internal reflection**.

cladding mode stripper Any device or material that promotes the radiation, and hence the loss, of cladding modes. *Note:* The primary polymer overcoat (primary coating) of modern optical communication fibers usually has an index of refraction slightly higher than that of the cladding, to strip off cladding modes after a few centimeters of propagation. *See also* **cladding, cladding mode, Maxwell's equations, mode, primary coating, Snell's law, total internal reflection.**

cladding ray *See* **cladding mode.**

cleave 1. In an optical fiber, a deliberate, controlled break, intended to create a perfectly flat endface, perpendicular to the longitudinal axis of the fiber. *Note:* A cleave is made by first introducing a microscopic fracture ("nick") into the fiber with a special tool, called a *"cleaving tool,"* which has a sharp blade of hard material, such as diamond, sapphire, or tungsten carbide. If proper tension is applied to the fiber as the nick is made, or immediately afterward (this may be done by the cleaving tool in some designs, or manually in other designs), the fracture will propagate in a controlled fashion, creating the desired endface. **2.** To break a fiber in such a controlled fashion. *Note:* A good cleave is required for a successful splice of an optical fiber, whether by fusion or mechanical means. Also, some types of optical connectors do not employ abrasives and polishers. Instead, they employ some type of cleaving technique to trim the fiber to its proper length, and produce a smooth, flat perpendicular endface. *See also* **hockey puck, microfinishing film.**

coherent light Light in which the phase relationship between points in a beam remains constant throughout the beam. *Note:* Because no realizable lightwave is ever perfectly coherent, one must, in practice, define the limits within which the degree of coherence is sufficient for the purpose in question. *See also* **incoherent light, light.**

collimate To convert a converging or diverging beam of light to a parallel beam. *See also* **convergence, divergence.**

collimator A device (some form of lens or mirror) which converts a converging or diverging beam of light to a parallel beam. *See also* **beam divergence, convergence, expanded-beam connector.**

composite cable An optical cable containing different types of optical fibers; e.g., single-mode and multimode. *See also* **duplex cable, hybrid cable, OFC, OFCP, OFCR, OFN, OFNP, OFNR, optical cable, optical fiber, pigtail** (definition 2), **zip-cord.**

concatenate To connect in series; e.g., two or more lengths of optical fiber. *See also* **connector, splice.**

concentricity error 1. In an optical fiber, the distance between the center of the core and the center of the cladding. 2. When a tolerance field is used to define the boundaries of the core and the cladding, the distance between the center of the pair of circles defining the core and the center of the pair of circles defining the cladding. *Synonym* **core-cladding offset.** *See also* **tolerance field.**

connector *See* **optical connector.**

convergence In optics, an approach, or closing, of the rays of a beam of light toward one another as they propagate; e.g., to a focus. *See also* **beam divergence, collimator, divergence.**

core The central part of an optical fiber, through which the optical signal propagates. *Note 1:* Strictly speaking, in certain cases a significant fraction of the energy in a bound mode does propagate in the cladding. Discussion of this may be found in advanced references. *Note 2:* The refractive index of the core must be slightly higher than that of the cladding. *See also* **graded-index profile, plastic-clad-silica fiber, refractive index, refractive index profile, Snell's law, step-index profile.**

core area The cross-sectional area of the core, defined (bounded) by the refractive boundary between the core and the cladding. *Note:* In an ideal communication fiber, the cross section of the core is usually perfectly circular. *See also* **area loss, core, tolerance field.**

core-cladding offset *See* **concentricity error.**

coupler *See* **directional coupler, optical connector, star coupler, T-coupler.** *See also* **splice.**

coupling efficiency The percentage or fraction of optical power transferred from one optical component (active or passive) to another. *See also* **coupling loss.**

coupling loss The power loss, usually expressed in decibels (dB), that occurs when light is transferred from one optical component (active or passive) to another. *See also* **angular misalignment loss, area loss, coupling efficiency, Fresnel reflection loss, gap loss, lateral offset loss, numerical aperture loss.**

critical angle The smallest angle of incidence, with respect to the normal at a refractive boundary, which will support total internal reflection. *See also* **Snell's law, total internal reflection.**

cutback technique One method of measuring the transmission loss of an optical fiber. *Note 1:* The procedure is performed by first energizing the fiber under test with a stable optical source. The level of optical power, emerging from the full length of the fiber under test, is measured. The fiber under test is then cut near the source, leaving a short pigtail, only a meter or two long, still energized by the source. The level of optical power emerging from this short length is measured. The power loss that occurred in the long length, removed by the cutting, is determined by the difference between the two power readings. *Note 2:* In a related method of measuring fiber loss, used in field practice, the fiber under test is disconnected from the optical source (test source or optical transmitter), and a short reference fiber having the same optical characteristics (core size, refraction profile and numerical aperture) is substituted. A reference reading, representing the launched optical power level, is taken at the other end of the short fiber. The fiber under test is then reconnected to the optical source, and a power reading taken at its far end. The difference between the reference reading and the reading at the distant end of the fiber under test represents the transmission loss of the fiber under test. *Note 3:* These methods of measuring loss are straightforward and easy to perform, but suffer from inaccuracies that usually indicate a higher normalized transmission loss than a more accurate technique would yield. If a number of fibers so measured are concatenated (connected or spliced in series), the total loss of the concatenated fibers (not including connector and/or splice losses) will usually be lower than would be expected from summing the losses of the individual fibers. *See also* **optical power meter, optical source, optical time-domain reflectometer.**

cutoff frequency In any active or passive device, the frequency at which the transfer function falls below a specified level. *Note:* In electronics practice, the specified level is usually taken to be the half-power, or 3-dB, point. *See also* **bandwidth, bandwidth• distance product, transfer function.**

dark current The electrical current that flows, under given bias conditions, in a photosensitive device (detector) when there is no incident radiation. *See also* **avalanche photodiode (APD), germanium photodiode, photocurrent, photodiode, positive-intrinsic-negative (PIN) diode, silicon photodiode.**

detection In communication practice, the recovery of the original modulating signal from an electrical or electromagnetic carrier. *Note:* Conventional radio waves are usually detected by heterodyning (coherent reception/detection). In this method of reception/detection, the received signal is mixed, in some type of nonlinear device, with a signal from a local oscillator, to produce an intermediate frequency (beat frequency), from which the modulating signal is recovered (detected). The inherent instabilities of available optical sources have, until relatively recently, prevented practical use of coherent reception/detection in optical communication receivers. At present, coherent optical receivers, employing sophisticated technology, are just beginning to emerge from the laboratory into the field. Virtually all existing optical receivers employ direct detection; that is, the received optical signal impinges directly onto a detector. Direct detection is less sensitive than coherent detection. *See also*

avalanche photodiode (APD), baseband modulation, germanium photodiode, modulation, modulator, optical mixing, photocurrent, silicon photodiode.

detector Any device used to recover the original modulating signal from an electrical or electromagnetic carrier. *Note:* The detector used in optical communication is normally an avalanche photodiode (APD) or positive-intrinsic-negative (PIN) diode. *See also* **avalanche photodiode (APD), bandwidth** (definition **2**, *Note 6*)**, detection, germanium photodiode, positive-intrinsic-negative (PIN) diode, silicon photodiode.**

dichroic mirror (filter) A mirror, or filter, that reflects one or more optical bands or wavelengths and transmits others, while maintaining a nearly zero coefficient of absorption for all wavelengths of interest.

dielectric An electrical insulator; a substance in which an electric field can be maintained with zero or nearly zero power consumption.

direct detection *See* **detection.**

directional coupler In optical communication, a three- or four-port passive optical coupler. *Note:* In a three-port device, a single optical input may be distributed to two outputs, in a ratio determined by the construction of the coupler. Alternatively, two inputs may be combined into a single output. In the case of the four-port device, two inputs may be combined into each of two outputs. *Synonyms* **optical directional coupler, optical splitter, splitter.** *See also* **star coupler, T-coupler.**

dispersion **1.** Any phenomenon in which electromagnetic wave propagation parameters are dependent upon wavelength. **2.** In an optical communication fiber, temporal spreading of the signal as a function of wavelength. *Note 1:* It is usually expressed in picoseconds per kilometer of fiber length, per nanometer of line width of the optical source. *Note 2:* The two major dispersion mechanisms in an optical fiber are *"material dispersion"* and *"waveguide dispersion."* Material dispersion occurs by virtue of the fact that different wavelengths propagate at different velocities through the bulk material (glass) of which the fiber is made. Because the optical signal necessarily has a finite spectral width (line width), not all of its component wavelengths propagate along the fiber at precisely the same velocity, resulting in temporal spreading of the signal. In the first (850-nanometer) window, material dispersion amounts to approximately 100 picoseconds (0.1 nanosecond), per nanometer of optical bandwidth, per kilometer of fiber length. In the second (1.3-μm) window, it approaches zero. In the third (1.55-μm) window, it again increases, but is still small compared to the first window. Waveguide dispersion is extremely small and is of interest only in single-mode fibers. Because the velocity of propagation in such fibers depends on the ratio α/λ, where α is the core radius and λ is the wavelength, a small spreading occurs in an optical signal of finite bandwidth, even in the absence of material dispersion. In a realizable fiber, material dispersion is always present to some degree, but with proper fiber design and construction, waveguide dispersion and material dispersion may be made to cancel one another over a very narrow band of wavelengths. *Note 3:* The term *"dispersion"* should not be confused with the term *"distortion."* *"Dispersion"* refers only to signal degradation that is attributable to wavelength-dependent phenomena. *Note 4:* The terms *"intermodal dispersion," "modal dispersion"* and *"multimode dispersion"* are incorrect and should not be used. Intermodal phenomena are associated with distortion. *Note 5:* The term *"chromatic dispersion"* is redundant and should not be used. *See also* **dispersion-shifted fiber, index of refraction, minimum-dispersion window, multimode distortion.**

dispersion-limited operation *See* **bandwidth-limited operation.**

dispersion-shifted fiber An optical fiber that has its minimum-dispersion window shifted, by the addition of dopants, to coincide with its minimum-attenuation window. *Note 1:* In such fibers, the engineering tradeoff is a slight increase in the minimum attenuation coefficient. *Note 2:* This type of fiber is intended for broadband telecommunication applications over very long distances, where wide bandwidth and low transmission loss are both of paramount importance. *See also* **dispersion, dopant, minimum-dispersion window, minimum-loss window, silica.**

distortion 1. A change in the shape of the signal waveform, which change occurs during transmission over a communication link or through a device. 2. Of an optical fiber, a change in the shape of the signal waveform, which change occurs during transmission over the fiber. *Note:* A number of different mechanisms may contribute to distortion of the signal during transmission over an optical fiber. *See also* **bandwidth-limited operation, dispersion, multimode distortion.**

distortion-limited operation *See* **bandwidth-limited operation**

divergence In geometric optics, a spreading of the rays of a beam away from one another as they propagate. *See also* **beam divergence, convergence, expanded-beam connector.**

dopant An impurity added to an optical medium to change its optical properties. *Note:* Dopants are used in optical fibers to control the refractive index profile and other refractive properties of the fiber. *See also* **dispersion-shifted fiber, refractive index, refractive index profile, silica.**

duplex cable An optical cable composed of two fibers. *See also* **composite cable, hybrid cable, OFC, OFCP, OFCR, OFN, OFNP, OFNR, optical cable, optical fiber, pigtail** (definition 2), **zip-cord.**

edge-emitting LED An LED that has a physical structure superficially resembling that of an injection laser diode, operated below the lasing threshold and emitting incoherent light. *Note:* Edge-emitting LEDs have a relatively small beam divergence, and thus are capable of launching more optical power into a given fiber than are the more conventional surface-emitting LEDs. *See also* **incoherent light, injection laser diode, Lambertian source, light, light-emitting diode (LED).**

electrical bandwidth *See* **bandwidth.**

electro-optic Referring to an electro-optic effect. *Note 1:* there are several electro-optic effects, which are phenomena in which an electromagnetic wave interacts with an electrical field, or with matter under the influence of an electrical field. Two of the most important electro-optic effects having application as modulation mechanisms in optical communication are the *"Kerr effect,"* (in which birefringence is induced) and the *"Pockels effect,"* (in which birefringence is modified). *Note 2:* The terms *"electro-optic"* and *"optoelectronic"* are not synonymous and should not be so used. *See also* **modulation, modulator, optoelectronic.**

EMD *Abbreviation for* **equilibrium mode distribution.**

equilibrium length The length of multimode fiber necessary to establish equilibrium mode distribution (EMD). *Note:* It varies from fiber to fiber and may range from a fraction of a kilometer to more than a kilometer. *See also* **equilibrium mode distribution.**

equilibrium mode distribution (EMD) That condition in a multimode fiber wherein after propagation has taken place for a certain distance, called the *"equilibrium length,"* the relative power distribution among modes becomes statistically constant and remains so for the course of further propagation down the fiber. *Note 1:* In practice, the equilibrium length may vary from a fraction of a kilometer to more than a kilometer. *Note 2:* After the equilibrium length has been traversed, the numerical aperture of the fiber's output is independent of the numerical aperture of the optical source (beam) that drives the fiber. This is because of mode coupling and stripping, primarily by small perturbations in the fiber's geometry which result from the manufacturing and cabling processes. *Note 3:* An alternative way of visualizing the equilibrium mode distribution is that condition in which the numerical aperture of a beam energizing the fiber at its input equals the numerical aperture of the output beam. *Note 4:* In the ray-optics analogy, the equilibrium mode distribution may be loosely thought of as a condition in which the "outermost rays" in the fiber core are stripped off by such phenomena as microbends, and only the "innermost rays" continue to propagate. In a typical 50-μm core multimode graded-index fiber, light propagating under equilibrium conditions occupies essentially the middle seven-tenths of the core and has a numerical aperture approximately seven-tenths that of the full numerical aperture of the fiber. This is why in-line optical attenuators based on the principle of gap loss may be ineffective or induce a lower-than-rated loss if they are inserted near the optical receiver. To be fully effective, such attenuators should be inserted near the optical transmitter, where the core is fully filled. *Synonym* **equilibrium mode power distribution.** *See also* **equilibrium length, gap-loss attenuator, mode coupling.**

expanded-beam connector A optical fiber connector that employs a miniature positive lens to collimate the diverging cone of light emitted by an optical fiber. *Note 1:* A similar lens in the mating connector reconverges the collimated light to a focus at the core of the connecting fiber. *Note 2*: The expanded-beam connector has the advantage that the large cross-sectional area of the expanded beam is relatively insensitive to lateral misalignment, including that caused by connector wear. The connector may thus be re-mated many times without appreciable deterioration in performance. *Note 3:* The engineering tradeoff of the expanded-beam connector is that the alignment of the fiber end, relative to the focal point of the miniature lens, is extremely critical. *See also* **beam divergence, collimator, convergence, divergence.**

fan out *Synonym* **break out.**

FDDI *Abbreviation for* **fiber distributed data interface.**

fiber amplifier A device that amplifies an optical signal directly, without first converting it back to an electrical signal. *Note:* The optical signal is passed through a special fiber that has been doped, e.g., with erbium, and which is continuously pumped (irradiated) with a laser, to achieve Raman amplification of the signal. *See also* **optical repeater.**

fiber bandwidth *See* **bandwidth.**

fiber *Synonym* **optical fiber.**

fiber buffer (tube) *Synonym* **buffer (tube).**

fiber distributed data interface (FDDI) An interface standard, defined by the American National Standards Institute (ANSI), for an optical-fiber-based dual counter-rotating broadband (100 Mbps each) token-ring digital communication network. *See also* **synchronous optical network (SONET).**

fiber optics The branch of optics concerned with the transmission of light through thin fibers (filaments) of transparent dielectric materials such as glass or plastic. *See also* **Maxwell's equations.**

fiber transfer function *See* **transfer function.**

first window Of silica-based optical fibers, the transmission window at approximately 830 to 850 nanometers. *See also* **dispersion-shifted fiber, minimum-dispersion window, minimum-loss window, second window, third window, window.**

flooding compound A substance surrounding the buffer tubes of an optical cable, to prevent water intrusion into the interstices in the event of a breach of the jacket. *See also* **gel.**

f-number (f/#, f-#) The ratio of the effective focal length of a lens to the diameter of the lens. *Synonym* **f-ratio.** *See also* **numerical aperture.**

Fresnel reflection Reflection that takes place at the boundary between two optical media having different indices of refraction; e.g., an glass-air boundary such as the end of an optical fiber. *Note 1:* For a normal ray, the Fresnel reflection coefficient is obtained from the following formula:

$$r = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

where n_1 is the index of the medium having the higher index of refraction and n_2 is the index of the medium having the lower index of refraction. *Note 2:* For a glass-air interface, n_2 may be considered equal to unity. *See also* **Fresnel reflection loss, Snell's law.**

Fresnel reflection loss A loss of optical power that takes place especially at a pair of mated connectors, but also to a lesser degree at splices, as a result of Fresnel reflection. *Note 1:* The effect is normally greatest at mated connectors because of the boundary conditions at the small air gap between the mating fibers. In some applications Fresnel reflection is alleviated by the use of an index-matching gel to eliminate the air space. *Note 2:* In splices, if the refractive indices of the mating fibers do not match perfectly, Fresnel reflection will also occur. *Note 3:* When mechanical splices are secured by an adhesive, an optical adhesive having a refractive index approximating that of the mating fibers is used to minimize Fresnel reflection loss. *Synonyms* **Fresnel loss, reflection loss.** *See also* **angular misalignment loss, area loss, Fresnel reflection, gap loss, lateral offset loss, numerical aperture loss.**

full width half maximum (FWHM) One way of defining or expressing the extent of a function. *Note 1:* It is expressed as the difference between the values of the independent variable at which the dependent variable is one-half its maximum value. *Note 2:* It is commonly used to express the spectral width (line width) of optical sources used in communication systems. *Synonym* **full width at half maximum.** *See also* **passband, peak emission wavelength, spectral width.**

furcate *Synonym* **break out.**

fusion splice An optical fiber splice (permanent joint) made by carefully aligning the mating fibers under a microscope and fusing (welding, melting) them together, usually with an electric arc. *See also* **cleave, mechanical splice, optical connector.**

FWHM *Abbreviation for* **full width half maximum.**

G *Abbreviation for* **giga.**

gap loss 1. The power loss that occurs when an optical signal is transferred from one fiber to another that is axially aligned with it, but longitudinally separated from it. *Note:* This allows light from the "transmitting" fiber to spread out as it leaves the fiber endface. When it strikes the "receiving" fiber, some of the light will enter the cladding, where it is quickly lost. **2.** An analogous form of coupling loss that occurs between an optical source, e.g., an LED, and an optical fiber. *Note:* Gap loss is not usually significant at the optical detector, because the sensitive area of the detector is normally somewhat larger than the cross section of the fiber core. Unless the separation is substantial, all light emerging from the fiber, even though it diverges, will still strike the detector. *See also* **angular misalignment loss, area loss, Fresnel reflection loss, gap-loss attenuator, lateral offset loss, numerical aperture loss.**

gap-loss attenuator An optical attenuator, inserted in-line in the fiber path, which attenuator exploits the principle of gap loss to reduce the optical power level (e.g., to prevent saturation of the receiver). *Note:* Gap-loss attenuators should be used in-line near the optical transmitter. *See also* **equilibrium mode distribution** (*Note 4*), **gap loss.**

gel 1. Index-matching material in the form of a gel. **2.** A substance, resembling petroleum jelly in viscosity, that surrounds a fiber, or multiple fibers, enclosed in a loose buffer tube. *Note:* This gel serves to lubricate and support the fibers in the buffer tube. It also prevents water intrusion in the event the buffer tube is breached. *See also* **flooding compound.**

geometric optics The analytical treatment of light propagation as rays perpendicular to the electromagnetic wavefront. *Note:* The rays may be represented schematically by lines perpendicular to the electromagnetic wavefront. *Synonyms* **geometrical optics, ray optics.**

germanium photodiode A germanium-based PN- or PIN-junction photodiode. *Note 1:* Such photodiodes are useful for direct detection of optical wavelengths from approximately 1 μm to several tens of μm. *Note 2:* Germanium-based detectors are noisier than silicon-based detectors. Silicon-based detectors are therefore normally preferred for wavelengths shorter than 1 μm. *See also* **avalanche multiplication, avalanche photodiode (APD), dark current, photoconductivity, photocurrent, photodiode, positive-intrinsic-negative (PIN) diode, silicon photodiode.**

giga- **(G)** SI prefix denoting one billion (10^9). *Note:* Pronounced jig'-uh. *See also* **mega-, micro-, nano-, pico-.**

glass 1. In the strict sense, a state of matter. **2.** In optical communication, any of a number of noncrystalline, amorphous inorganic substances, formed (by heating) from metallic or semiconductor oxides or halides, and used as the material for fibers. *Note:* The most common glasses are based on silicon dioxide (SiO_2). *See also* **dopant, preform, silica.**

graded-index fiber *See* **graded-index profile.** *See also* **refractive index profile, step-index profile.**

graded-index profile A refraction profile in which the refractive index of the core changes as a function of distance from the fiber axis. *Note 1:* In an ordinary multimode graded-index fiber, the ideal profile is very nearly parabolic in shape, the refractive index being greatest on the fiber axis. *Note 2:* The parabolically graded profile partially compensates for multimode distortion in multimode fibers. *See also* **multimode distortion, refractive index, refractive index profile, step-index profile.**

guided ray Loosely, a ray that is confined to the core of an optical fiber and propagates with minimum loss. *Synonym* **bound ray.** *See also* **bound mode, mode.**

heterodyning *See* **optical mixing.**

hockey puck Colloquial term for a fixture used to facilitate the manual finishing of the endfaces of certain types of optical fiber connectors. *Note:* The fixture consists of the appropriate mating sleeve for the connector in question, mounted at right angles to, and in the center of, a disk of stainless steel or other hard material. When the unfinished connector, secured to the optical cable, is mounted in the fixture, excess material (fiber end, bead of adhesive material, and excess connector length, if present) protrudes from the opposite side of the disk. The excess is then ground away as the fixture is manually swept to and fro, usually in a figure-8 pattern, in contact with a piece of microfinishing film which is in turn supported by a rigid flat substrate. Two to four grades of microfinishing film, with abrasive particles ranging in size from 15 μm to 0.3 μm, are commonly used. *See also* **abrasive, cleave, microfinishing film.**

hybrid cable An optical cable that also contains one or more components intended to carry electric current. *See also* **composite cable, duplex cable, OFC, OFCP, OFCR, OFN, OFNP, OFNR, optical cable, pigtail** (definition **2**), **zip-cord.**

ILD *Abbreviation for* **injection laser diode.**

incoherent light Light which lacks a constant phase relationship between points in the beam. *See also* **coherent light, light.**

index-matching material A substance, usually a liquid, cement (adhesive), or gel, which has an index of refraction that closely approximates that of an optical fiber, and is used to reduce Fresnel reflection at the fiber endface. *Synonyms* **gel, index-matching gel.** *See also* **gel.**

index of refraction *Synonym* **refractive index.**

index profile *Synonym* **refractive index profile.**

infrared The region of the electromagnetic spectrum that lies between the longest visible waves (approximately 700 nanometers) and the shortest microwaves (approximately 1 millimeter). *See also* **light, ultraviolet.**

injection laser diode (ILD) A laser that uses a forward-biased semiconductor junction as the active (lasing) medium. *Note:* These devices are used in optical communication where relatively high launched power and/or a narrow spectral width are required. An ILD normally has a spectral width of no more than a few nanometers. *Synonyms* **laser diode, semiconductor laser diode.** *See also* **light-emitting diode (LED).**

integrated optical circuit (IOC) A hybrid or monolithic optical circuit having both active and passive components and performing the dual functions of the electrical-optical interface and signal processor.

intermodal delay distortion *Synonym* **multimode distortion.**

intermodal dispersion *Incorrect synonym for* **multimode distortion.** *See also* **dispersion, multimode distortion.**

intermodal distortion *Synonym* **multimode distortion.**

IOC *Abbreviation for* **integrated optical circuit.**

joint Of optical fibers, a point of concatenation, by either a splice or a connector.

Kevlar ™ *See* **aramid (yarn).**

Lambertian source An optical source having an intensity that is directly proportional to the cosine of the angle from which it is viewed. *Note:* Conventional (surface-emitting) LEDs are approximately Lambertian. They have a large beam divergence. This results in a radiation pattern that resembles a sphere. Thus, most of their total optical output is not coupled into communication fibers. *See also* **edge-emitting LED.**

laser *Acronym for* **light amplification by stimulated emission of radiation.** A device that produces highly coherent optical radiation by means of population inversion and an optical cavity that produces positive feedback. *See also* **injection laser diode.**

laser diode *Synonym* **injection laser diode.**

lateral offset loss A form of loss of optical power at a splice or connector, caused by a lateral (transverse) offset of the mating fiber cores, which offset causes an imperfect transfer of the optical signal from the "transmitting" fiber to the "receiving" fiber. *Note:* The effect of a given amount of lateral offset will depend on other parameters such as the relative diameters of the respective cores. For example: if, because of manufacturing tolerances, the "transmitting" core is smaller than the "receiving" core, the effect will be less than if both cores were the same size. *See also* **angular misalignment loss, area loss, Fresnel reflection loss, gap loss, numerical aperture loss.**

lay length In a communication cables (including optical cables) having the transmission media wrapped helically around a central member, the longitudinal distance along the cable required for one complete helical wrap; i.e., the total cable length divided by the total number of wraps (turns). *Note 1:* In many optical cable designs, the lay length is shorter than in metallic cables of similar diameter, to avoid overstressing the fibers during the pulling associated with the installation operation. *Note 2:* The wraps (turns) that are referred to should not be confused with the twists given twisted metallic pairs (wires) to reduce electromagnetic coupling. Pairs of optical fibers are not given such twists. *See also* **optical cable.**

leaky ray Of an optical fiber, in the ray optics analogy, a ray for which Snell's law predicts total internal reflection, but which suffers loss because of the finite size of the optical wave and the small radius of the fiber core. *See also* **axial ray, bound mode, cladding mode, meridional ray, skew ray.**

LED *Abbreviation for* **light-emitting diode.**

light In the strictest sense, the portion of the electromagnetic spectrum that is visible to the normal human eye (approximately 400 nanometers to 700 nanometers). *Note:* The term is now customarily held to include the infrared spectrum to a wavelength of tens of micrometers. *See also* **coherent light, incoherent light, infrared, ultraviolet.**

light-emitting diode (LED) A solid-state diode employing a forward-biased PN junction that emits incoherent light. *Note:* LEDs have a spectral width on the order of 35 to 100 nanometers, FWHM. *See also* **edge-emitting LED, incoherent light, injection laser diode (ILD), Lambertian source, light.**

line width *See* **spectral width.**

link *See* **optical link.**

loose buffer *See* **buffer (tube).**

M *Abbreviation for* **mega.**

macrobend A large-radius bend in an optical fiber, such as might be found in a splice organizer tray or an optical cable that has been bent. *Note:* A macrobend will result in no significant radiation loss if it is of sufficiently large radius. The definition of "sufficiently large" depends on the type of fiber. Single-mode fibers have a low numerical aperture (typically less than 0.15) and are therefore are more susceptible to bend losses than other types. Normally, they will not tolerate a minimum bend radius of less than 2.5 to 3 inches (6.5 to 7.5 cm). (Certain specialized types of single-mode fibers, however, can tolerate a far shorter minimum bend radius without appreciable loss.) A graded-index multimode fiber having a core diameter of 50 μm and a numerical aperture of 0.20 will typically tolerate a minimum bend radius of not less than 1.5 inches (3.8 cm). The fibers commonly used in customer-premises applications (62.5-μm core) typically have a relatively high numerical aperture (approximately 0.27) and can tolerate a bend radius of less than an inch (2.5 cm). *See also* **microbends, numerical aperture, tap.**

matching gel *See* **index-matching material.**

material dispersion *See* **dispersion.**

Maxwell's equations A set of partial differential equations, developed by James Clerk Maxwell (ca. 1873), which expand upon and unify the laws of Ampere, Faraday, and Gauss, and which form the foundation of modern electromagnetic theory. *Note:* They describe and predict the behavior of electromagnetic waves in free space, in dielectrics, and at conductor-dielectric boundaries. *See also* **geometric optics, mode.**

mechanical splice 1. A splice (permanent joint) accomplished by aligning the mating fibers in some kind of mechanical fixture. *Note 1:* The fibers may be secured by mechanical means or with an optical adhesive. *Note 2:* When the fibers are secured by mechanical means, the gap between them is usually filled with an index-matching gel to reduce Fresnel reflection. Likewise, the optical adhesives that are used in conjunction with mechanical splices are formulated to have a refractive index that approximates that of the glass, and also serve to reduce Fresnel reflection. *See also* **concatenate, connector, fusion splice, mechanical splice.**

mega- (M) SI prefix denoting one million (10^{6}). *See also* **giga-, micro-, nano-, pico-.**

meridional ray A non-axial ray that passes through the fiber axis (i.e., intersects it at an angle), as opposed to a skew ray, which does not. *See also* **axial ray, cladding mode, leaky ray, skew ray.**

micro- (μ) SI prefix denoting one-millionth (10^{-6}). *Note:* The informal abbreviation "u" is sometimes employed when the symbol "μ" is not available in the font being used. *See also* **giga-, mega-, nano-, pico-.**

microbends 1. In an optical fiber, very small, sharp curves imparted by the processes of coating, cabling, etc. 2. Analogous curves that appear, e.g., in a thin film optical waveguide, as in an integrated optical circuit, caused by imperfections. *Note:* Microbends cause radiative losses and mode coupling. *See also* **macrobend.**

microfinishing film A film of dimensionally stable plastic, to which are adhered carefully graded abrasive or polishing powders (particles) having dimensions in the micrometer or submicrometer range. *Note:* Microfinishing films resemble sandpaper, but have much smaller abrasive or polishing particles. They are used commercially to shape and/or polish machined parts. They are also used to finish the endfaces of certain types of optical connectors. *See also* **abrasive, hockey puck.**

micrometer (μm) The SI unit of length equal to one-millionth of a meter (10^{-6} meter). *Note 1:* Pronounced micro'-meter. *Note 2:* The micrometer is commonly used to express optical wavelengths greater than 1000 nanometers. *Note 3:* The informal abbreviation "um" is sometimes employed when the symbol "μ" is not available in the font being used. *Note 4:* The obsolete term *"micron"* is often used as a synonym for *"micrometer."* The former was used prior to adoption of the latter by international agreement.

micron (**μm**) *Deprecated synonym for* **micrometer.** *Note 1:* Although technically obsolete, the term *"micron"* is still very widely used. *Note 2:* The informal abbreviation "um" is sometimes used when the symbol "μ" is not available in the font being used.

millimicron *Deprecated synonym for* **nanometer.**

minimum-dispersion window **1.** The window of an optical fiber at which material dispersion is very small. *Note 1:* In silica-based fibers, this window occurs at a wavelength of approximately 1.3 μm. *Note 2:* The minimum-dispersion window may be shifted toward the minimum-loss window (1.55 μm) by the addition of dopants. **2.** In a single-mode fiber, the window at which material and waveguide dispersion cancel one another, resulting in extremely wide bandwidth (i.e., extremely low dispersion) over a very narrow range of wavelengths. *Synonym* **zero-dispersion window.** *See also* **dispersion, dispersion-shifted fiber, distortion, first window, minimum-loss window, multimode distortion, refractive index, second window, third window, window.**

minimum-loss window The transmission window of an optical fiber at which the attenuation coefficient is at or near the theoretical (quantum-limited) minimum. *Note 1:* If the losses from various mechanisms are plotted on a single graph as a function of wavelength, it is the wavelength at which the Rayleigh-scattering attenuation curve and the infrared-phonon-absorption curve intersect. *Note 2:* For silica-based fibers, this window occurs at approximately 1.55 μm. *See also* **phonon absorption, Rayleigh scattering.**

mixing *See* **optical mixing.**

modal dispersion *Incorrect synonym for* **multimode distortion.** *See also* **dispersion, multimode distortion.**

modal distortion *Synonym* **multimode distortion.**

mode In any cavity composed of conductor-dielectric boundaries (e.g., a conventional microwave cavity) or dielectric-dielectric boundaries (e.g., an optical fiber or waveguide), any electromagnetic field distribution that satisfies Maxwell's equations and the given boundary conditions. *Note:* Modes are represented mathematically by the eigenvalues of the solutions of Maxwell's equations for the wavelength in question and the given boundary conditions. *See also* **bound mode, cladding mode, Maxwell's equations.**

mode coupling In a multimode optical fiber, a power exchange among propagating modes. *Note:* This may result from a number of causes, such as imperfections in fiber geometry, microbends, etc. *See also* **equilibrium mode distribution, Maxwell's equations.**

mode scrambler Any device used to induce mode coupling in an optical fiber. *Note:* One practical use for such a device is to obtain an even distribution of propagating modes from an optical source, for making transmission loss measurements.

modulation A controlled variation with time of any characteristic of an electromagnetic wave, for the purpose of transmitting information. *Note 1:* Conventional optical transmitters employ what is called *"amplitude intensity modulation"* (a redundant term), or simply *"intensity modulation"* (preferred). There are no sidebands in the normally understood sense of the word, because conventional optical sources, even the so-called "monochromatic" ones, are too unstable in frequency to permit ordinary sideband generation and heterodyne detection. *Note 2:* Even if the electrical signal of interest is used to frequency-modulate an electrical carrier wave before being transmitted by the lightwave (an "FM" lightwave transmission system), it is still the intensity of the lightwave that is modulated by the FM carrier wave to convey the information. In this case, the "information," as far as the lightwave is concerned, is the electrical FM carrier wave. The lightwave is varied in intensity at an instantaneous rate corresponding to the instantaneous frequency of the electrical carrier wave. *Note 3:* At the time of preparation of this document, coherent lightwave transmission systems, employing sophisticated technology, are just beginning to emerge from the laboratory into the field. *See also* **detection, detector, modulator.**

modulator Any device used to perform a controlled variation with time of any characteristic of an electromagnetic wave, for the purpose of transmitting information. *See also* **detection, detector, electro-optic, modulation.**

monochromatic Of a lightwave, consisting of only one wavelength (color). *Note:* In practice, no lightwave is ever perfectly monochromatic. There is always a band of frequencies (wavelengths), however narrow. When used, the term is understood to mean an extremely narrow band of optical wavelengths, on the order of a fraction of a nanometer. *See also* **full width half maximum, spectral width.**

monomode fiber *Synonym* **single-mode fiber.**

multifiber cable An optical cable having two or more fibers, each of which is capable of serving as an independent optical transmission channel. *See also* **optical cable.**

multimode dispersion *Incorrect synonym for* **multimode distortion.** *See also* **dispersion, multimode distortion.**

multimode distortion A distortion mechanism, occurring in multimode fibers, in which the signal is spread in time because the velocity of propagation of the optical signal is not the same via all modes. *Note 1:* In the ray-optics analogy, multimode distortion in a step-index optical fiber may be compared to multipath propagation of a radio signal. The direct signal is distorted by the arrival of the reflected signal a short time later. In the step-index optical fiber, light rays taking more direct paths through the fiber core (i.e., those which undergo the fewest reflections at the core-cladding boundary) will traverse the length of the fiber sooner than those rays which undergo more reflections. This results in distortion of the signal. *Note 2:* Because of its similarity to dispersion in its effect on the optical signal, multimode distortion is sometimes incorrectly referred to as *"intermodal dispersion," "modal dispersion,"* or *"multimode dispersion."* Such usage is incorrect because multimode distortion is not a truly dispersive effect. *Note 3:* Multimode distortion limits the bandwidth of multimode fibers. For example, a typical step-index fiber with a 50-μm core would be limited to approximately 20 megahertz for a one-kilometer length (i.e., a bandwidth of 20 megahertz•kilometer). *Note 4:* Multimode distortion may be considerably reduced, but never completely eliminated, by the use of a core having a graded refractive index. The bandwidth of a typical off-the-shelf graded-index multimode fiber, having a 50-μm core, may approach 1 gigahertz-kilometer, although multimode graded-index fibers having bandwidths approaching 3 gigahertz-kilometer have been produced. *Synonyms* **intermodal distortion, modal distortion.** *See also* **bandwidth, dispersion, graded-index profile, step-index profile, transfer function.**

multimode optical fiber An optical fiber that supports more than one bound mode of propagation. *See also* **bandwidth, graded-index profile, Maxwell's equations, mode, multimode distortion, step-index profile.**

n *Abbreviation for* **nano.**

NA *Abbreviation for* **numerical aperture.**

nano- (n) SI prefix denoting one-billionth (10^{-9}). *See also* **giga-, mega-, micro-, pico-.**

nanometer The SI unit of length equal to one-billionth of a meter (10^{-9} meter). *Note:* It is commonly used to express optical wavelengths of less than one micrometer. *See also* **micrometer.**

noncircularity *Synonym* **ovality.**

numerical aperture (NA) Of an optical fiber, a figure of merit that expresses the extent to which it can accept, into its bound mode(s), rays which strike it at an angle with respect to its longitudinal axis. *Note 1:* In an imprecise but commonly used sense, numerical aperture is defined as the sine of the acceptance angle (one-half of the acceptance cone) of an optical fiber. *Note 2:* More precisely, numerical aperture is the sine of the acceptance angle of the largest cone of meridional rays that can enter or exit an optical element (including an optical fiber), multiplied by the index of refraction of the medium in which the cone is situated. *Note 3:* In a step-index optical fiber, $NA = (n_1^2 - n_2^2)^{1/2}$, where n_1 is the refractive index of the core and n_2 is the refractive index of the cladding. *Note 4:* In a graded-index optical fiber, $NA = (n_1^2 - n_2^2)^{1/2}$, where n_1 is the nominal refractive index at the center of the core and n_2 is the refractive index at the core-cladding boundary. *Note 5:* The numerical aperture of an optical fiber is a measure of its ability to capture light (i.e., excite its bound modes) from an optical source or a mating fiber. The higher the numerical aperture, the more light the fiber is capable of capturing; i.e., the wider the angle, with respect to its longitudinal axis, from which it will accept an incoming ray. *See also* **acceptance angle, beam divergence, f-number, macrobend, vertex angle.**

numerical aperture loss A loss of optical power that occurs at a splice or a pair of mated connectors when the numerical aperture of the "transmitting" fiber exceeds that of the "receiving" fiber, even if the cores are precisely the same diameter and are perfectly aligned. *Note 1:* The higher numerical aperture of the transmitting fiber means that it will emit a larger cone of light than the receiving fiber is capable of accepting, resulting in a coupling loss. *Note 2:* In the opposite case of numerical aperture mismatch, where the transmitting fiber has the lower numerical aperture, no numerical aperture loss will occur, because the receiving fiber will be capable of accepting light from any bound mode of the transmitting fiber. *See also* **angular misalignment loss, area loss, Fresnel reflection loss, gap loss, lateral offset loss.**

OFC *Abbreviation for* **optical fiber, conductive.** *Note:* This is the designation given by the National Fire Protection Association (NFPA) to interior optical fiber cables which contain at least one electrically conductive, non-current-carrying component, such as a metallic strength member or vapor barrier, and which are not certified for use in plenum or riser applications. *See also* **composite cable, duplex cable, hybrid cable, OFCP, OFCR, OFN, OFNP, OFNR, optical cable, pigtail** (definition **2**), **zip-cord.**

OFCP *Abbreviation for* **optical fiber, conductive, plenum.** *Note:* This is the designation given by the National Fire Protection Association (NFPA) to interior optical fiber cables which contain at least one electrically conductive, non-current-carrying component such as a metallic strength member or vapor barrier, and which are certified for use in plenum applications. *See also* **composite cable, duplex cable, hybrid cable, OFC, OFCR, OFN, OFNP, OFNR, optical cable, pigtail** (definition **2**), **zip-cord.**

OFCR *Abbreviation for* **optical fiber, conductive, riser.** *Note:* This is the designation given by the National Fire Protection Association (NFPA) to interior optical fiber cables which contain at least one electrically conductive, non-current-carrying component such as a metallic strength member or vapor barrier, and which are certified for use in riser applications. *See also* **composite cable, duplex cable, hybrid cable, OFC, OFCP, OFN, OFNP, OFNR, optical cable, pigtail** (definition 2), **zip-cord.**

OFN *Abbreviation for* **optical fiber, nonconductive.** *Note:* This is the designation given by the National Fire Protection Association (NFPA) to interior optical fiber cables which contain no electrically conductive component, and which are not certified for use in plenum or riser applications. *See also* **composite cable, duplex cable, hybrid cable, OFC, OFCP, OFCR, OFNP, OFNR, optical cable, pigtail** (definition 2), **zip-cord.**

OFNP *Abbreviation for* **optical fiber, nonconductive, plenum.** *Note:* This is the designation given by the National Fire Protection Association (NFPA) to interior optical fiber cables which contain no electrically conductive component, and which are certified for use in plenum applications. *See also* **composite cable, duplex cable, hybrid cable, OFC, OFCP, OFCR, OFN, OFNR, optical cable, pigtail** (definition 2), **zip-cord.**

OFNR *Abbreviation for* **optical fiber, nonconductive, riser.** *Note:* This is the designation given by the National Fire Protection Association (NFPA) to interior optical fiber cables which contain no electrically conductive component, and which are certified for use in riser applications. *See also* **composite cable, duplex cable, hybrid cable, OFC, OFCP, OFCR, OFN, OFNP, optical cable, pigtail** (definition 2), **zip-cord.**

optical amplifier *See* **fiber amplifier, optical repeater.**

optical cable A communication cable containing one or more optical fibers (waveguides). *Note:* It may be an all-fiber cable, or contain both optical fibers and metallic conductors. One possible use for the metallic conductors is the transmission of electric power for repeaters. *See also* **composite cable, duplex cable, hybrid cable, OFC, OFCP, OFCR, OFN, OFNP, OFNR, optical fiber, pigtail** (definition 2), **zip-cord.**

optical connector A demountable device for attaching an optical cable (fiber) to another, or to an active device such as a transmitter. *Note 1:* A connector is distinguished by the fact that it may be disconnected and reconnected, as opposed to a splice, which permanently joins two fibers. *Note 2:* Optical connectors are sometimes erroneously referred to as *"couplers."* Such usage is incorrect and is to be avoided. *See also* **concatenate, directional coupler, fusion splice, mechanical splice, splice, splice loss, star coupler** (definition 2), **T-coupler.**

optical coupler *See* **directional coupler, star coupler** (definition 1), **T-coupler.**

optical fiber 1. In the strict sense, a dielectric filament of carefully controlled design, composition and construction intended for use as an electromagnetic waveguide at optical frequencies. 2. In a broad sense, any dielectric filament that guides light. *See also* **all-silica fiber, optical cable, optical waveguide, plastic-clad-silica fiber, preform.**

optical fiber transfer function *See* **transfer function.**

optical heterodyning *See* **optical mixing.**

optical link An optical transmission channel, including any repeaters or regenerative repeaters, designed to connect two electronic or optoelectronic communication terminals. *Note:* Sometimes held to include the terminal optical transmitter and receiver, especially in the case of a communication link utilizing separate electronic terminals originally designed for metallic transmission, and retrofitted for optical transmission. *See also* **fiber amplifier, integrated optical circuit, optical power budget, optical receiver, optical repeater, optical transceiver, optical transmitter.**

optical mixing Optical beating; the mixing (heterodyning) of two lightwaves (incoming signal and local oscillator) in a nonlinear device to produce a beat frequency low enough to be further processed by conventional electronic circuitry. *Note:* This is the optical analog of heterodyne reception of radio signals. *Synonym* **optical heterodyning.** *See also* **detection.**

optical power budget In an optical fiber communication link, the difference between the optical power that is launched by a given transmitter into the fiber, and the minimum optical power that is required by the receiver for a specified level of performance. *Note 1:* This is usually expressed as the ratio, in decibels (dB), of the of the launched power to the minimum power required at the input to the receiver. *Note 2:* The amount of optical power launched by a given transmitter depends on the nature of its active optical source (LED, including the type of LED, or laser diode) and the type of fiber, including such parameters as core diameter and numerical aperture. *Note 3:* When a power budget is specified, it must be specified for the particular fiber that is to be used. If it is specified by the manufacturer for a different fiber (or what is worse, for a given distance only), the user must first ascertain, from the manufacturer or by testing, what the optical power budget is for the type of fiber in question, and for the required level of performance. In addition to the transmission loss, including any splices and connectors, allowance should be made for at least several decibels of power margin, to compensate for component aging and to allow for future splices in the event of a cable break. *See also* **attenuation-limited operation, bandwidth-limited operation, fiber amplifier, integrated optical circuit, optical link, optical power meter, optical receiver, optical repeater, optical source, optical transceiver, optical transmitter.**

optical receiver An apparatus that receives an optical signal, detects it, and processes the resulting electrical signal as required. *See also* **fiber amplifier, integrated optical circuit, optical link, optical repeater, optical transceiver, optical transmitter.**

optical regenerator *See* **optical repeater.**

optical repeater A device that receives an optical signal, detects it, amplifies the resulting electrical signal, and reconverts the signal to optical form for retransmission at a higher power level. *Note 1:* Although the term "repeater" originated in the early days of telegraphy when electromechanical relays were used to regenerate ("repeat") telegraph signals, its use was continued through the era of analog telephony and may refer to a purely electronic analog amplifier as well as the optical communication device described in the definition above. *Note 2:* The optical repeater may, in the case of a digital signal, reshape and retime the pulses before their conversion back to optical form for retransmission. Such a device is also known as a *"regenerative repeater" or "regenerator." Synonym* **optical amplifier.** *See also* **fiber amplifier.**

optical source **1.** In an optical transmitter or repeater, the optoelectronic device (LED or injection laser diode) that performs the conversion of the electrical signal to the corresponding optical signal. **2.** A device that generates a stable optical signal for the purpose of making optical transmission loss measurements. *See also* **cutback technique, injection laser diode, light, light-emitting diode, optical power meter.**

optical splitter *See* **directional coupler.**

optical time-domain reflectometer (OTDR) An optoelectronic instrument used to define the attenuation characteristics of an optical fiber. *Note 1:* It works by launching a series of short (a few tens of nanoseconds, or shorter) optical pulses into the fiber, and measuring the intensity of the backscattered signal as a function of the time interval that has elapsed since the launch. From this information a plot is made of optical power level versus distance along the fiber, giving a transmission loss profile of the fiber, and an estimate of its total length. *Note 2:* The OTDR is a useful tool for estimating (and only estimating) the fiber attenuation coefficient and overall loss, and losses caused by local defects, splices, and connectors, and the distance to such defects, splices or connectors, or to a fiber break. *See also* **cutback technique, optical power meter, optical source, Rayleigh scattering.**

optical transceiver An apparatus that combines the functions of an optical transmitter and optical receiver. *See also* **fiber amplifier, integrated optical circuit, optical link, optical receiver, optical repeater, optical transmitter.**

optical transmitter 1. An apparatus that accepts an electrical signal as its input, processes this signal, and uses it to modulate an optoelectronic device (LED or laser diode) to produce an optical signal capable of being transmitted via an optical fiber. 2. A similar apparatus that employs an optical collimator to transmit the optical signal through the atmosphere or free space. *See also* **fiber amplifier, integrated optical circuit, optical link, optical receiver, optical repeater, optical transceiver.**

optical waveguide 1. *Synonym* **optical fiber.** 2. Any device or component that guides optical energy; e.g., a thin dielectric channel on a substrate as part of an integrated optical circuit. *See also* **integrated optical circuit, Maxwell's equations, mode.**

optoelectronic 1. Pertaining to any device that functions an electrical-to-optical or optical-to-electrical transducer. 2. Pertaining to any instrument that employs such a device in its operation. *Note:* The term *"optoelectronic"* is not a synonym for *"electro-optic,"* and should not be so used. *See also* **electro-optic, optical time-domain reflectometer (OTDR).**

organizer *See* **splice organizer.**

OTDR *Abbreviation for* **optical time-domain reflectometer.**

ovality In an optical fiber, the degree of deviation of the cross section of the core-cladding boundary, or cladding, from perfect circularity. *Note:* For purposes of computing ovality, the cross section is assumed to be elliptical. Ovality is defined as:

$$\frac{2(L_M - L_m)}{L_M + L_m}$$

where L_M is the length of the major axis of the ellipse and L_m is the length of the minor axis of the ellipse. The above fraction is usually multiplied by 100, to express ovality as a percentage. *Synonym* **noncircularity.** *See also* **concentricity error, tolerance field.**

p *Abbreviation for* **pico.**

passband That portion of spectrum, between limiting frequencies or wavelengths, which is transmitted with minimum relative loss or maximum relative gain. *Note:* The limiting frequencies (wavelengths) are defined as those at which the relative (normalized) intensity or power decreases to a specified fraction of the peak frequency (wavelength), often one-half (3 dB). The slope of the roll-off (decrease) may also be defined, often in dB/octave. *See also* **absorption band, bandwidth, full width half maximum (FWHM), peak emission wavelength, spectral width.**

passive star *See* **star coupler.**

PCS fiber *Abbreviation for* **plastic-clad-silica fiber.**

peak emission wavelength Of an optical emitter such as an LED or laser diode, the optical emission line (wavelength) having the greatest intensity. *See also* **full width half maximum, passband, spectral width.**

peak spectral emission *See* **peak emission wavelength.**

peak wavelength 1. *Synonym* **peak emission wavelength.** 2. Of an optical (bandpass) filter, that wavelength which suffers the lowest loss. *See also* **full width half maximum (FWHM), passband, spectral width.**

phonon A quantum of vibrational energy. *See also* **phonon absorption, photon, Rayleigh scattering.**

phonon absorption Absorption of light by its conversion to vibrational energy. *Note:* Phonon absorption determines the fundamental (quantum) limit of attenuation in silica-based glasses in the far infrared region. *See also* **photon, photon absorption, Rayleigh scattering.**

photoconductivity An increase in electrical conductivity, exhibited by some materials, which increase results when free carriers are generated by the electronic transitions caused by the absorption of photons. *See also* **avalanche multiplication, avalanche photodiode (APD), dark current, germanium photodiode, photocurrent, photodiode, positive-intrinsic-negative (PIN) diode, silicon photodiode.**

photocurrent The electrical current that flows in a photoconductive device as the result of exposure to radiant energy. *See also* **avalanche multiplication, avalanche photodiode (APD), dark current, germanium photodiode, photoconductivity, photodiode, positive-intrinsic-negative (PIN) diode, silicon photodiode.**

photodiode A solid-state diode in which the flow of electric current is produced or enhanced by the absorption of light. *Note:* Photodiodes may be fabricated from silicon- or germanium-based materials. These are treated elsewhere herein. Special ternary or quaternary materials, based on such elements as arsenic, gallium, indium and phosphorous, also may be used to fabricate photodiodes for specific applications and wavelengths. *See also* **avalanche multiplication, avalanche photodiode (APD), dark**

current, germanium photodiode, photoconductivity, photocurrent, positive-intrinsic-negative (PIN) diode, silicon photodiode.

photon A quantum of electromagnetic energy. *See also* **phonon, photon noise, quantum noise.**

photon noise In an optical communication link, noise attributable to the statistical nature of optical quanta. *Synonym* **quantum noise.** *See also* **quantum-limited operation.**

pico- (p) SI prefix for one trillionth (10^{-12}). *Note:* Pronounced peek'oh. *See also* **giga-, mega-, micro-, nano-.**

pigtail 1. A short length of optical fiber that is permanently affixed to an active device (e.g, an LED or laser diode), and is used to couple the device, with a splice or connector, to a longer fiber. **2.** A short length of single-fiber cable, usually tight-buffered, that has an optical connector on one end and a length of exposed fiber at the other end. *Note:* The exposed fiber of the pigtail is then spliced to one fiber of a multifiber trunk (arterial) cable, to enable the multifiber cable to be "broken out" into individual single-fiber cables that may be connected to a patch panel or an input or output port of an optical receiver or transmitter. *See also* **break out, breakout cable, optical cable, optical connector, splice.**

PIN diode *Abbreviation for* **positive-intrinsic-negative diode.**

plastic-clad-silica (PCS) fiber An optical fiber that has a silica-based core and a plastic cladding. *Note 1:* The plastic cladding should not be confused with the primary polymer overcoat of an all-silica-based fiber. *Note 2:* PCS fibers are not normally used for telecommunication purposes. *Synonym* **polymer-clad-silica fiber.** *See also* **all-silica fiber, optical fiber, primary coating.**

polymer-clad-silica fiber *Synonym* **plastic-clad-silica fiber.**

positive-intrinsic-negative (PIN) diode A semiconductor diode that has a relatively large intrinsic (i.e., undoped or neutral) region between the P- and N-doped regions. *Note:* Photons are absorbed in the intrinsic region and create electron-hole pairs that are separated by the applied bias voltage, thus generating a current in the load circuit. *Synonym* **positive-intrinsic-negative (PIN) photodiode.** *See also* **avalanche photodiode (APD), dark current, germanium photodiode, photocurrent, photodiode, silicon photodiode.**

power budget *See* **optical power budget.**

preform A large glass rod, approximately 4 centimeters in diameter by two meters long, from which an optical fiber is drawn. *Note:* The refractive index profile of the preform determines the profile of the fiber that is drawn from it. *See also* **all-silica fiber, plastic-clad-silica fiber.**

primary coating The plastic overcoat in intimate contact with the cladding of an optical fiber, applied during the manufacturing process. *Note 1:* This coating typically has an outside diameter of approximately 250 to 500 μm, and serves to protect the fiber from mechanical damage and chemical attack. It also enhances its optical properties by stripping off cladding modes, and in the case where multiple fibers are used inside a single buffer tube, it suppresses cross-coupling of optical signals from one fiber to another. *Note 2:* This coating should not be confused with a tight buffer, or the plastic cladding of a plastic-clad-silica (PCS) fiber. *Synonyms* **primary polymer coating, primary polymer overcoat.** *See also* **buffer (tube), plastic-clad-silica (PCS) fiber, preform.**

profile *See* **refractive index profile.**

quantum-limited operation In an optical communication system, operation in which the minimum detectable signal is limited by quantum (photon) noise. *Note:* This is an ideal condition not realizable in practice. *See also* **phonon absorption, photon noise, quantum noise, Rayleigh scattering, shot noise.**

quantum noise In optical communication, of a lightwave, the noise attributable to the statistical nature of optical quanta (light). *Note:* It represents the fundamental limit of the achievable signal-to-noise ratio of an optical communication system. This limit is never achieved in practice. *Synonym* **photon noise.** *See also* **photon noise, quantum-limited operation, shot noise.**

radiation angle Half the vertex angle of the cone of light emitted by a device; e.g., an optical fiber or optical source such as an LED or laser diode. *See also* **beam divergence, numerical aperture.**

radiation mode Of an optical fiber, an unguided mode. *Note:* Radiation modes may be compared to refracted rays in the ray optics analogy. *See also* **bound mode, cladding mode, leaky ray, unbound mode.**

ray A geometric representation of a lightwave by a line normal to the electromagnetic wavefront; i.e., in the direction of propagation of the wave. *See also* **axial ray, cladding mode, geometric optics, leaky ray, meridional ray, skew ray.**

Rayleigh scattering Scattering of light, which scattering is caused refractive index inhomogeneities that are small compared to the wavelength in question. *Note 1:* The amount of scattering is inversely proportional to the fourth power of the wavelength. *Note 2:* Rayleigh scattering represents the dominant fundamental mechanism limiting optical fiber transparency at short (ultraviolet and visible) wavelengths, and is present to some degree at all wavelengths used for optical communication. *See also* **optical time-domain reflectometer, phonon absorption.**

ray optics *Synonym* **geometric optics.**

receiver *See* **optical receiver.**

refraction The bending of a non-normal beam of light as it passes through the boundary (interface) between two media having different indices of refraction, or through a medium having an index of refraction that is a continuous function of position; e.g., the core of a multimode graded-index fiber. *See also* **graded-index profile, refractive index, step-index profile.**

refraction profile *Synonym* **refractive index profile.**

refractive index (n, η) Of an optical medium, the ratio of the velocity of light in a vacuum, to that in the medium. *Note:* The refractive index varies with different materials, and also varies with wavelength in a given material. For example, in ordinary silica-based glasses, the refractive index is highest for violet light. It decreases in a nearly linear fashion (linear slope) through the visible red and into the infrared region just beyond. This phenomenon gives rise to material dispersion of the optical signal. Further in the infrared region, the slope (rate of change of refractive index with wavelength) gradually decreases, becoming nearly zero at a wavelength of approximately 1.3 μm. This is the so-called "zero-dispersion" or "minimum-dispersion" wavelength, where the slope exhibits a point of inflection and gradually becomes steeper. *Synonym* **index of refraction.** *See also* **dispersion, dispersion-shifted fiber, minimum-dispersion window, refractive index profile, velocity of light.**

refractive index profile **1.** Of an optical fiber, a plot of the fiber's refractive index as a function of the distance from the fiber axis. *Note:* The usual practice is to express the distance from the fiber axis on the abscissa ("x" direction), and the refractive index on the ordinate ("y" direction). **2.** An analogous plot of the refractive index of any optical waveguide; e.g., a thin-film waveguide in an integrated optical circuit. *Synonym*

refraction profile. *See also* **graded-index profile, multimode distortion, refractive index, step-index profile.**

regenerator *See* **optical repeater.**

repeater *See* **fiber amplifier, optical repeater.**

rip cord Of an optical cable, a parallel cord of strong yarn that is situated under the jacket(s) of the cable for the purpose of facilitating jacket removal preparatory to splicing or breaking out. *Note:* The rip cord is exposed by carefully removing or severing a portion of the jacket near the end of the cable. It is then grasped with the fingers, or more usually, with a tool such as a pair of pliers, and pulled to sever the jacket for the remainder of the desired distance. *See also* **aramid (yarn).**

relative spectral width *See* **spectral width.**

scattering **1.** Of propagation in an optical fiber, a change in direction or polarization, which change results from interaction of the lightwave with with refractive-index microinhomogeneities in the fiber material. **2.** Any change in the direction of propagation, or polarization, of an electromagnetic wave, attributable to its interaction with particulate matter, or refractive-index inhomogeneities, in the medium in which it travels. *See also* **backscattering, phonon absorption, Rayleigh scattering.**

second window Of silica-based optical fibers, the transmission window at approximately 1.3 μm. *Note:* This is the minimum-dispersion window in silica-based glasses. *See also* **dispersion-shifted fiber, first window, minimum-dispersion window, minimum-loss window, third window, window.**

semiconductor laser diode *Synonym* **injection laser diode.**

shot noise Quantum noise caused by electric current fluctuations attributable to the discrete nature of charge carriers. *See also* **photon noise, quantum-limited operation.**

SI *Abbreviation for* **Système International d'Unités.** *Note:* This is the International System of Units, on which the modern metric system is based.

silica Silicon dioxide (SiO_2). *Note 1:* It may occur in crystalline or amorphous form, and occurs naturally in impure forms such as quartz and sand. *Note 2:* It is the basic material of which the most common optical communication fibers are presently made. *See also* **dispersion-shifted fiber, dopant, glass, graded-index profile, step-index profile.**

silicon dioxide (SiO_2) *See* **silica.**

silicon photodiode A silicon-based PN- or PIN-junction photodiode. *Note 1:* Such photodiodes are useful for direct detection of optical wavelengths shorter than approximately 1 μm. *Note 2:* Because of their greater bandgap, silicon-based photodiodes are quieter than germanium-based photodiodes, but germanium photodiodes must be used for wavelengths longer than approximately 1 μm. *See also* **avalanche multiplication, avalanche photodiode (APD), dark current, germanium photodiode, photoconductivity, photocurrent, photodiode, positive-intrinsic-negative (PIN) diode.**

single-mode fiber An optical fiber that supports only one mode of electromagnetic propagation. *Note 1:* Propagation via a single mode avoids the bandwidth-limiting effects of modal distortion. *Note 2:* Single-mode fibers have small cores (approximately 8 μm), and a relatively low numerical aperture. Thus, they capture less light from a given optical source than multimode fibers. This is partially compensated by the fact that because of their lower dopant levels, they have lower transmission losses than multimode fibers. *Note 3:* With the exception of certain specialized designs, single-mode fibers are more sensitive than multimode fibers to bending losses. *Note 4:* Single-mode fibers are more difficult to splice, and exhibit higher losses through a given connector, than multimode fibers. For long-distance broadband telecommunication applications, these disadvantages are more than offset by lower transmission losses and greater bandwidth, making the single-mode fiber the logical choice for such applications. *Synonyms* **monomode fiber, unimode fiber.** *See also* **graded-index profile, Maxwell's equations, mode, multimode fiber, step-index profile.**

skew ray In a multimode optical fiber, any bound ray, that in propagating, does not pass through (intersect) the fiber axis. *See also* **axial ray, cladding mode, leaky ray, meridional ray.**

Snell's law A law of geometric optics that defines the amount of bending that takes place when a light ray strikes a refractive boundary (e.g., an air-glass interface) at a non-normal angle. *Note 1:* The law states that:

$$n_i(\text{Sin}\,\Theta_i) = n_r(\text{Sin}\,\Theta_r)$$

where n_i is the index of refraction of the medium in which the incident ray travels, Θ_i is the angle (with respect to the normal at the refractive boundary) at which the incident ray strikes the boundary, n_r is the index of refraction of the medium in which the refracted ray travels, and Θ_r is the angle (with respect to the normal at the refractive boundary) at which the refracted ray travels. The incident ray and refracted ray travel in the same plane, on opposite sides of the normal. *Note 2:* If a ray travels from a medium of lower refractive index into a medium of higher refractive index, it is bent toward the normal; if it travels from a medium of higher refractive index to a medium of lower index, it is bent away from the normal. *Note 3:* If the incident ray travels in a medium of higher refractive index toward a medium of lower refractive index at such an angle that Snell's law would call for the sine of the refracted ray to be greater than unity (a mathematical impossibility); i.e.,

$$\sin \Theta_r = [n_i/n_r] \sin \Theta_i$$

where $\sin \Theta_r > 1$, then the "refracted" ray in actuality becomes a reflected ray and is totally reflected back into the medium of higher refractive index, at an angle equal to the incident angle (and thus still "obeys" Snell's Law). This reflection occurs even in the absence of a metallic reflective coating (e.g., aluminum or silver) on the glass. This phenomenon is called *"total internal reflection."* The smallest angle of incidence, with respect to the normal at the refractive boundary, which angle will support total internal reflection, is called the *"critical angle."* *See also* **refraction, refractive index.**

SONET *Acronym for* **synchronous optical network.**

spectral bandwidth *See* **spectral width.**

spectral width A measure of the wavelength extent of a spectrum. *Note 1:* It may be expressed in absolute units, e.g., nanometers, between points that have an intensity that is a specified fraction of the intensity of the peak emission (or transmission) wavelength. *Note 2:* It is sometimes expressed as *"relative spectral width,"* $\delta\lambda/\lambda$, where $\delta\lambda$ is the absolute spectral width and λ is the peak emission (or transmission) wavelength in the same units, e.g., nanometers. *Synonyms* **line width, spectral bandwidth.** *See also* **full width half maximum (FWHM), peak emission wavelength.**

spectral window *See* **window.**

splice 1. To permanently join optical fibers, either by fusing (melting, welding) them together, or by aligning them in a mechanical device (fixture) and securing them, usually with some kind of adhesive. 2. A mechanical device that so joins optical fibers. *Note:* Such devices are sometimes erroneously referred to as *"couplers."* Such usage is to be avoided. 3. The joint itself. *See also* **directional coupler, fusion splice, mechanical splice, optical connector, star coupler, T-coupler.**

splice closure A usually weatherproof encasement, commonly made of tough plastic, that envelops the exposed area between spliced cables (i.e., where the jackets have been removed to expose the individual transmission media, optical or metallic, to be joined). *Note 1:* The closure usually contains some device or means to maintain continuity of the tensile strength members of the cables involved, and also may maintain electrical continuity of metallic armor, and/or provide external connectivity to such armor for electrical grounding. *Note 2:* In the case of optical cables, it also contains some type of splice organizer to facilitate the splicing process and protect the exposed fibers from mechanical damage. *Note 3:* In addition to the seals at its seams and and points of cable entry, the splice closure may be filled with an encapsulant to further retard the entry of water. *Synonym* **closure.** *See also* **fusion splice, mechanical splice, splice, splice organizer.**

splice loss Any loss of optical power at a splice, attributable to one or more mechanisms. *Note:* A practical splice, of physically realizable fibers, has losses attributable to a number of mechanisms, some of which are intrinsic to the fibers, and some of which are intrinsic to the method or device being used to join them. *See also* **angular misalignment loss, area loss, Fresnel reflection loss, fusion splice, gap loss, lateral offset loss, mechanical splice, numerical aperture loss, optical connector, splice.**

splice organizer In optical communication, a device that facilitates the splicing or breaking out of optical cables. *Note:* The organizer provides means to separate and secure individual buffer tubes and/or fibers or pigtails. It also provides means to secure mechanical splices or protective sleeves used in connection with fusion splices, and has means to contain the slack fiber that remains after the splicing process is completed. *See also* **break out, breakout cable, fusion splice, mechanical splice, optical cable, pigtail** (definition **2**), **splice, splice closure.**

splitter *See* **directional coupler.**

star coupler **1.** A passive optical coupler having a number of input and output ports, used in network applications. *Note:* An optical signal introduced into any input port is distributed to all output ports. Because of the nature of the construction of a passive star coupler, the number of ports is usually a power of 2; i.e., two input ports and two output ports (a "two-port" coupler, customarily called a *"directional coupler,"* or *"splitter"*); four input ports and four output ports (a "four-port" coupler); eight input ports and eight output ports (an "eight-port" coupler); etc. **2.** An analogous active device that employs individual optical transceivers, electrically interconnected, which transceivers usually consist of circuit cards plugged into a common chassis, and which drive the respective fibers feeding the various nodes. *Note 1:* An active star coupler has the advantage that it regenerates the optical signal before retransmitting it. Thus, it suffers no power penalty from passive splitting. The regeneration also has the effect of reducing overall pulse distortion attributable to the optical path, because only the path between a given node and the active star contributes to distortion, rather than the full path between nodes. *Note 2:* The electronic circuitry of the active star coupler may also contain means to avoid retransmitting a signal back to the originating node. This prevents the transmitting node from receiving an echo of its own transmission, which echo may be deleterious. *See also* **directional coupler.**

steady-state distribution *Synonym* **equilibrium mode distribution.**

step-index fiber *See* **step-index profile.** *See also* **graded-index profile, refractive index profile.**

step-index profile A refractive index profile that exhibits a uniform index of refraction throughout the fiber's core, and decreases abruptly at the core-cladding boundary. *Note:* The name arises from the fact that a cartesian plot of this refraction profile resembles a step. *See also* **graded-index profile, multimode distortion, refractive index profile.**

strength member Any component of a communication cable (metallic or optical), the function of which is to protect the transport medium (conductor or fiber) from excessive tensile and bending stresses during installation and while in service. *See also* **aramid (yarn), armor.**

surface reflection *See* **Fresnel reflection.**

synchronous optical network (SONET) A digital optical communication interface standard, based on a data rate of 51.840 Mbps, designated OC1 (optical carrier 1), with multiples up to OC48, for an aggregate data rate of 2.48832 Gbps. *See also* **fiber distributed data interface (FDDI).**

tap 1. Any device used to extract a portion of the optical power from a fiber. **2.** To extract a portion of the optical power from a fiber. *Note:* One method of tapping an optical fiber is to bend it to a relatively short radius, thus promoting radiation of a portion of the optical signal. *See also* **macrobend.**

T-coupler A passive optical coupler having three ports (three fibers). *Note 1:* Two inputs may be combined into one output; or one input, into two outputs. *Note 2:* The amount of coupling (percentage, or loss in decibels) between ports is determined by the design and construction of the coupler. *Synonym* **splitter.** *See also* **directional coupler, optical connector, splice, star coupler.**

third window Of silica-based optical fibers, the transmission window at approximately 1.55 μm. *Note:* This is the minimum-loss window in silica-based fibers. *See also* **first window, dispersion-shifted fiber, minimum-dispersion window, minimum-loss window, second window, window.**

tight buffer *See* **buffer (tube).**

time-domain reflectometer (optical) *See* **optical time-domain reflectometer (OTDR).**

tolerance field 1. Pertaining to the cross section of an optical fiber, when used to specify the respective diameters and ovalities of, and concentricity error between, the core and cladding; two concentric annular regions which define the core-cladding boundary and the cladding outer boundary. *Note:* Dimensions are usually in micrometers (μm). The larger annular region is defined by concentric circles of diameter $[D_C + \Delta D_C]$ and $[D_C - \Delta D_C]$, where D_C is the nominal diameter of the cladding and ΔD_C is the cladding diameter tolerance. The smaller annular region is defined by concentric circles of diameter $[D_c + \Delta D_c]$ and $[D_c - \Delta D_c]$, where D_c is the nominal diameter of the core and ΔD_c is the core diameter tolerance. When the core and cladding boundaries of the cross section of the fiber in question fall entirely within their respective defined areas, the fiber meets the specification. **2.** Of the cross section of a given optical fiber, when used to characterize the respective diameters and ovalities of the core and cladding, and the concentricity error between the core and cladding; two such pairs of circles, not necessarily concentric. *Note 1:* One pair characterizes the core, and the other pair, the cladding. The cladding *ovality* is characterized by the smallest circle that circumscribes its cross section, and the largest circle that fits within its cross section. (The cross section is assumed, to a first approximation, to be elliptical in shape, so these defining circles will be concentric.) The core cross section is characterized by an analogous pair of circles, also concentric with one another, but not necessarily with those defining the cladding cross section. *Note 2:* The distance between the centers of the two concentric pairs (core pair and cladding pair) defines the *offset* between the core and cladding (the *"core-cladding offset,"* also called the *"concentricity error"*). The width of the annulus defined by the cladding circles determines the ovality of the cladding, and the width of the annulus defined by the core determines the ovality of the core. *See also* **concentricity error, ovality.**

total internal reflection In the optical regime, the total reflection of a lightwave, even in the absence of a reflective coating, that occurs under certain conditions at a refractive boundary; e.g., a glass-air interface. *See also* **cladding mode, critical angle, Snell's law.**

transceiver *See* **optical transceiver.**

transfer function 1. Of an optical fiber, the complex mathematical function that expresses the ratio of the variation, as a function of modulation frequency, of the instantaneous power of the optical signal at the output of the fiber, to the instantaneous power of the optical signal that is launched into the fiber. *Note:* The optical detectors used in communication applications are square-law devices. Their output current is proportional to the input optical power. Because electrical power is proportional to current, when the optical power input drops by one-half (3 dB), the electrical power at the output of the detector drops by three-quarters (6 dB). **2.** The complex mathematical function that expresses the ratio of the output of a device (active or passive) to the input, as a function of frequency. *See also* **bandwidth.**

transmitter *See* **optical transmitter.**

trapped mode (ray) *Synonyms* **bound mode (ray), guided mode (ray).**

μ *Abbreviation for* **micro.** *Note:* The informal abbreviation "u" is sometimes employed when the symbol "μ" is unavailable in the font being used.

ultraviolet The region of the electromagnetic spectrum consisting of wavelengths shorter than the shortest visible light (approximately 400 nanometers), but longer than X-rays. *See also* **infrared, light.**

μm *Abbreviation for* **micrometer.** *Note:* The informal abbreviation "um" is sometimes employed when the symbol "μ" is unavailable in the font being used.

unbound mode A radiation or leaky mode; one that does not propagate with minimum loss. *See also* **bound mode, cladding mode, leaky ray, mode, radiation mode.**

unimode fiber *Synonym* **single-mode fiber.**

velocity of light (c) The velocity of an electromagnetic wave in free space, precisely 299,792,458 meters per second. *Note 1:* The preceding figure is precise because by international agreement the meter is now defined in terms of the velocity of light. *Note 2:* The velocity of an electromagnetic wave (light) is equal to the product of the wavelength and the frequency. *Note 3:* In any physical medium, the velocity of light will be lower than in free space. Since the frequency is not changed, the wavelength is also decreased. *See also* **dispersion, refractive index.**

vertex angle In an optical fiber, the angle formed by the extreme bound meridional rays accepted by the fiber, or emerging from it, equal to twice the acceptance angle; the angle formed by the largest cone of light accepted by the fiber or emitted from it. *See also* **acceptance angle, numerical aperture.**

video Adjective describing the bandwidth (data rate) necessary for the transmission of real-time television pictures. *Note 1:* The actual bandwidth required to transmit "real-time" television pictures will vary according to parameters such as the required resolution and the rate at which the information is refreshed. In the frequency domain, the term "video" normally implies a minimum bandwidth on the order of several megahertz. In the United States, a commercial broadcast television channel has a bandwidth of 6 megahertz, including audio carrier and guard bands. The actual video channel is approximately 4.2 megahertz wide, and is transmitted over a band approximately 5 megahertz wide, including the vestigial sideband. *Note 2:* When analog video signals are digitized, the resultant data may be processed ("compressed") by any of a number of techniques so that only changes are transmitted via the communication link. These techniques can substantially reduce the required data rate with respect to that required by simple pulse-code-modulation (PCM) systems.

waveguide *See* **optical waveguide.** *See also* **optical fiber.**

waveguide dispersion The temporal spreading of an optical signal as a function of wavelength, because of phenomena related to the geometry of the optical waveguide (fiber). *See also* **dispersion, distortion, multimode distortion.**

wavelength-division multiplexing (WDM) Any technique by which two or more optical signals of different wavelengths may be simultaneously transmitted in the same direction over one fiber, and then be separated by wavelength at the distant end. *See also* **bidirectional transmission.**

wavelength-division multiplexer (WDM) Any device used to accomplish wavelength division multiplexing.

WDM *Abbreviation for* **wavelength-division multiplexer, wavelength-division multiplexing.**

window A band of wavelengths at which an optical fiber is sufficiently transparent for practical use in communication applications. *Note 1:* This implies a wavelength, or band of wavelengths, at which the fiber is sufficiently free from undesired impurities that cause attenuation substantially in excess of the quantum-limited mechanisms (primarily Rayleigh scattering, which predominates at shorter wavelengths, and phonon absorption, which predominates at longer wavelengths). *Note 2:* In silica-based fibers, there are three windows suitable for optical communication. The *"first window"* is in the region around 830 to 850 nanometers, and has a minimum loss, in practical, cabled fibers, of approximately 3 dB per kilometer. It also has the highest material dispersion, approximately 100 picoseconds per nanometer of optical line width, per kilometer of fiber length. The *"second window,"* at a wavelength of approximately 1.3 μm, is the minimum-dispersion region, where material dispersion is nearly zero. Its transmission loss is typically less than 1 dB per kilometer. The *"third window"* is in the region around 1.55 μm. This window has the lowest transmission loss in silica-based fibers, approximately 0.25 dB per kilometer. *Note 3: "Dispersion-shifted"* fibers (single-mode) have their minimum-dispersion windows shifted, by the addition of dopants in the glass, toward the minimum-loss window. The engineering tradeoff is a slight increase in the minimum-loss attenuation. *See also* **dispersion, first window, phonon absorption, Rayleigh scattering, second window, third window, minimum-dispersion window.**

zero-dispersion window *See* **minimum-dispersion window, window.**

zip-cord In optical communication, a colloquial name for a two-fiber cable consisting essentially of two single-fiber cables having their jackets conjoined by a strip of jacket material. *Note 1:* This name is borrowed from electrical terminology referring to lamp cord. As with lamp cord, optical zip-cord may be easily furcated by slitting or tearing the two jackets apart, permitting the installation of optical connectors. *Note 2:* Zip-cord cables include both loose-buffer and tight-buffer designs. *See also* **duplex cable, composite cable, hybrid cable, OFC, OFCP, OFCR, OFN, OFNP, OFNR, optical cable, optical fiber, pigtail** (definition 2).

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